Appendix C
Tunnel Boring Machine Performance Concepts and Performance Prediction

This appendix provides information for tunnel designers concerning TBM performance specifications, test data for performance estimates, and estimating costs for TBM tunnels.

C-1. TBM Design and Performance Concepts

The focus of a site investigation and testing program is not just to support the tunnel design. Testing results and recommendations made must also sensitize the contractor to the site conditions before construction, a perspective that permits estimation of cost and schedule and supports the selection of appropriate excavation equipment. The tests used to characterize rock for excavation purposes are often different from tests utilized in other civil works and may depend on the excavation method. For comparison of several alignments, a simple inexpensive test may be sensitive enough to detect differences in boreability, identify problem areas, and give an estimate of thrust and torque requirements.

a. Principles of disc cutting. TBM design and performance predictions require an appreciation of basic principles of disc cutting. Figure C-1 illustrates the action of disc cutting tools involving inelastic crushing of rock material beneath the cutter disc and chip breakout by fracture propagation to an adjacent groove. The muck created in this process includes fine materials from crushing and chips from fracture. The fines are active participants in disc wear. Rock chips have typical dimensions of 15- to 25-mm thickness, widths on the order of the cutter disc groove spacing, and lengths on the order of two to four times the chip width. For efficient disc cutting by a TBM, several items are important including the following:

- The cutter indenting, normal force, and penetration must be sufficient to produce adequate penetration for kerf interaction and chip formation.

- Adjacent grooves must be close enough so that lateral cracks can interact and extend to create a chip.

- There must be a disc force component adequate to maintain cutter movement, in spite of the rolling resistance or drag associated with the penetration process.

b. Normal forces. Disc penetration is affected by the applied TBM thrust. The average thrust, or normal force (F_n), per cutter is calculated as:

$$F_n = N_c \, p_c' \, \pi \, d_c^2 \, / \, (4 \, n) \qquad \text{(C-1)}$$

where N_c is the number of thrust cylinders; p_c' is the net applied hydraulic pressure; d_c is the diameter of each cylinder piston; and n is the number of cutters in the array. Thrust delivered to the cutters is less than that calculated based on operating hydraulic pressure. If the backup system for a TBM is towed behind the TBM during mining, then this loss of thrust should be subtracted, as should friction losses from contact between the machine and the rock. For full shields this loss can be very high and may ultimately stop forward progress if ground pressures on the shield are larger than can be overcome by available thrust. The net average cutter normal force can easily be 40 percent less than the calculated gross force. For very hard rock, thrust limits may severely restrict the penetration rate.

c. Disc rolling force. Disc rolling is affected by supplied machine power and cutterhead rotation. The average rolling force per cutter, F_r, is calculated as:

$$F_r = P' \, / \, (2\pi \; n \; r \; R_c) \qquad \text{(C-2)}$$

where P' is the net delivered power; r is the cutterhead rotation rate (rpm); and R_c is the weighted average cutter distance from the center of rotation. Losses on installed power can also be significant, and overall torque system efficiency is generally about 75 percent. Available F_r can be further reduced when motor problems temporarily decrease the available torque, sticky muck clogs the cutterhead and muck buckets resulting in torque losses from friction and drag against rotation, or with a "frozen" or blocked cutter with a seized bearing. In fact, for many TBMs operated in weak to moderately strong rock, the torque capacity limits the penetration rate. This influence is decreased in recent TBMs designed with variable cutterhead rotation rates and higher powered motors. Load capacity of a sidewall gripper system can also limit the level of thrust and torque that can be applied. With weak rock, the grippers may slide or develop local bearing capacity failure in the sidewall rock. In weak rock, wood cribbing may be required if overbreak is more extensive than the gripper cylinder stroke. These problems are particularly severe when mining from weak into hard rock when high thrust is desired for efficient cutting the grippers must bear on low-strength rock. For shielded TBMs, the strength of the lining may limit operating thrust and torque.

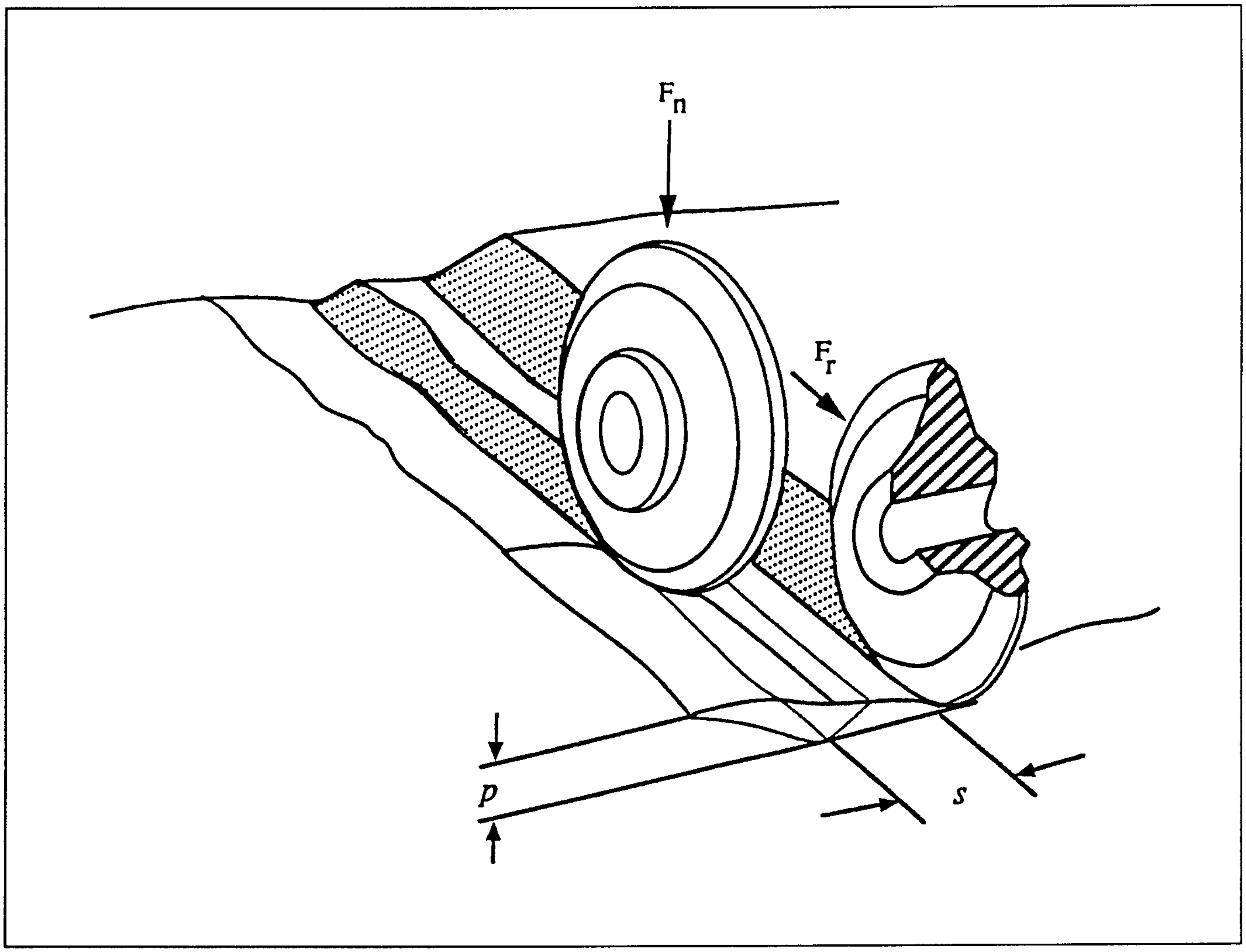

Figure C-1. Disc force and geometry for Kerf cutting

d. Disc force penetration index. TBM operating conditions are not uniform, and it is not likely that the disc forces calculated above are actually developed for any particular cutter. However, it is convenient to develop a model for disc force prediction in the context of these average forces, as well as average disc spacing *(s)* and penetration per revolution (*PRev*). The interaction of F_n and F_r, and the resulting penetration is indicated in Figure C-2. The changing slope corresponds to a transition in dominance between crushing and chip formation and has been called the "critical thrust": unless force of this magnitude can be applied, chipping between grooves will not occur. The critical thrust is directly related to rock strength or hardness and increases with cutter spacing and disc edge width. Although these force/penetration relationships are known to be nonlinear, several parameters have been defined based on ratios derived from force/penetration plots. The ratio of F_r to F_n has been defined as the cutting coefficient (C_c), and the ratio of F_n to *PRev* is defined as the penetration index (R_f). Therefore:

$$C_c = \frac{F_r}{F_n} \text{ and } R_f = \frac{F_n}{PRev} \tag{C-3}$$

e. Research on TBM cutting mechanics has yielded the following important observations:

- *PRev* is primarily controlled by F_n; i.e., with sufficient delivered power, cutterhead rpm does not strongly affect PRev.

- Optimized cutting is possible when the ratio of spacing(s) to *PRev* (*s/p*) is on the order of about 8 to 20 for a wide variety of rock units.

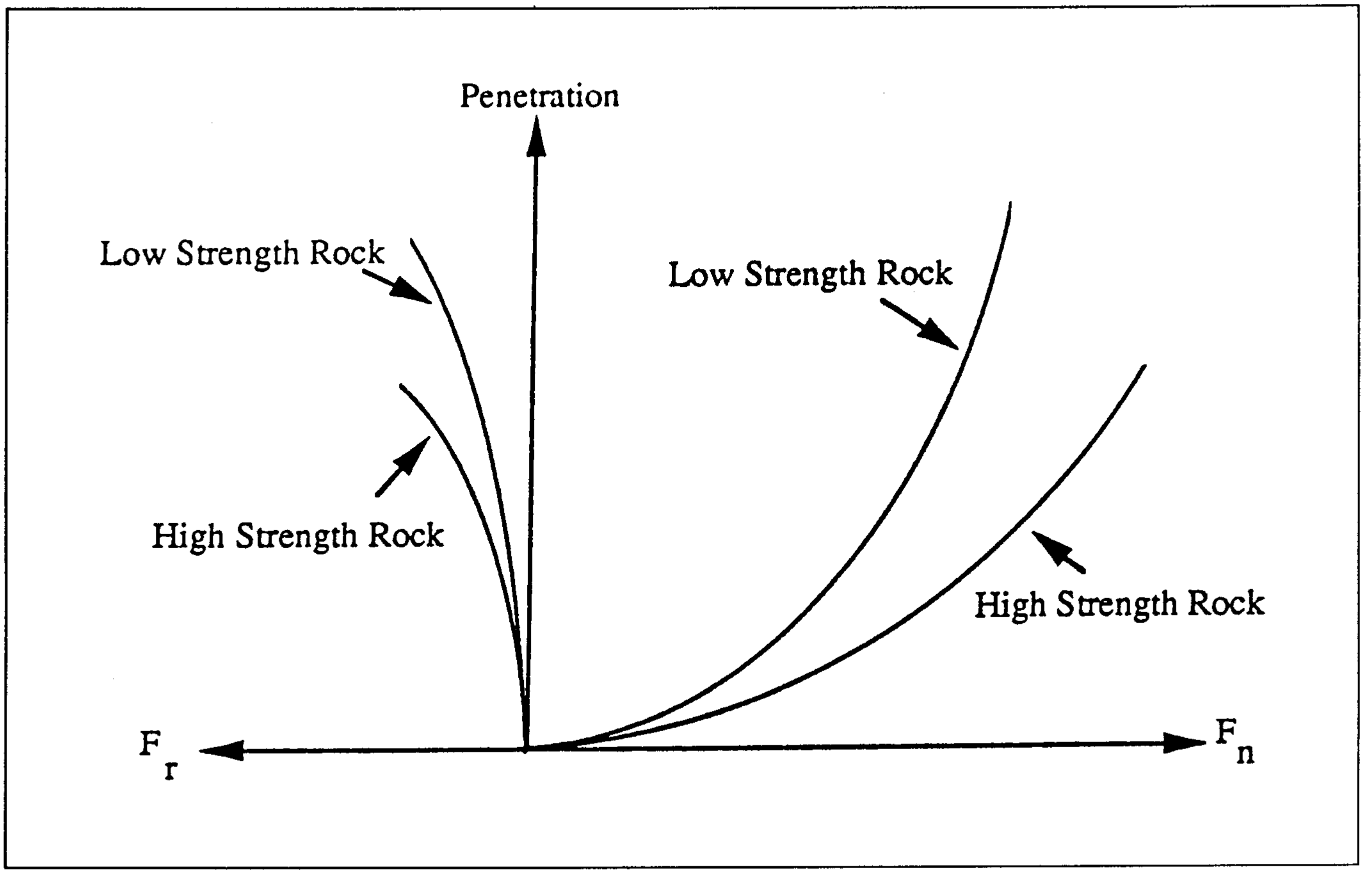

Figure C-2. General plot of disc cutter force variation with penetration for high- and low-strength rocks

- A less than optimum but still satisfactory cutting rate *s/p* ratio may occur in weaker rock due to high penetrations at lower cutter forces.

- For strong rock, high critical thrust results in reduced penetration and increased *s/p* ratios, and acceptable mining rates are difficult to achieve.

- For porous or microfractured rock, indentation results in large volumes of crushed and potentially abrasive material and reduced chip formation.

C-2. TBM Penetration Rate Prediction From Intact Rock Properties

The most important independent variables for TBM design include installed power, cutterhead rpm, thrust, and disc spacing. Each parameter influences the resulting penetration rate. In practice, average disc spacing has been designed in a limited range between 60 and 90 mm. Fixed design conditions include disc rolling velocity and disc tool loading limits. Given accepted limits on disc velocity and loading and the general range of target *s/p* ratios used in practice, a method to predict relationships between F_n, F_r, and *PRev* would permit a TBM design with adequate power and thrust to achieve desired penetration rates.

a. Prediction methods. Many efforts have been made to correlate laboratory index test results to TBM penetration rate. Prediction equations are either empirically derived or developed with a theoretical basis using force equilibrium or energy balance theories. Simplified assumptions of disc indentation geometry and contact zone stress distribution are made, and coefficients derived from correlations with case history information are used. Most prediction methods agree on trends, but empirical methods are case-specific in terms of geology and machine characteristics. However, a general statement of caution about the case history databases should be made. Prediction methods that do not consider operating conditions of thrust and torque cannot be applied to projects where equipment operations vary. The condition of the cutters can also have a significant effect on performance, since worn or blunted discs present wider contact areas on indentation and require higher forces for a given level of penetration. Some data bases include performance with single, double, and triple disc cutters, a variation that greatly affects disc edge loading and spacing/penetration ratios. Finally, low-thrust and low-torque mining through poor ground or alignment curves may result in reduced penetration rates.

b. Penetration index tests. As examples of index tests used in correlations, several prediction approaches utilize static indentation tests performed on confined rock specimens. A second group of index tests can be called "hardness" tests, including Shore hardness, Scleroscope hardness, Taber abrasion hardness, Schmidt hammer rebound hardness (H_R), and Total Hardness (H_T), which is calculated as the product of H_R and the square root of the Taber abrasion hardness. Dynamic impact tests have also been developed for application to TBM performance prediction. These include Rock Impact Hardness (RIH), Coefficient of Rock Strength (CRS), and the Swedish Brittleness Test (S_{20}), which is incorporated in the prediction method developed by the Norwegian Institute of Technology (NTH). Many "drillability" and "abrasivity" index tests have also been developed; each requires specialized equipment. The CERCHAR (the Laboratoire du Centre d'Études at Recherches des Charbonnages de France) test has been used in assessing abrasivity, and mineralogical abrasiveness measures, including quartz content and Moh's hardness scale, are used.

c. Rock strength testing.

(1) Empirically derived prediction equations have also incorporated results from "conventional" rock strength testing. The rock property most widely used in performance prediction has been the uniaxial compressive strength (UCS) primarily because of the availability of UCS test results. However, UCS may not be the ideal parameter for TBM performance prediction unless in situ variability of UCS (or of index test results) is evaluated.

(2) Rock tensile strength, most often measured in a Brazil test, may also be used for machine performance prediction. Test results can be used for weak rock to evaluate whether brittle behavior will occur on disc indentation and to evaluate rock strength anisotropy.

(3) Rock fracture toughness and other fracture material properties (such as the critical energy release rate or critical crack driving force) have great potential application for machine performance prediction. However, few tests have been performed at tunneling projects so the correlations performance demonstrated to date must be considered preliminary.

(4) Other descriptive properties are also evaluated during site investigations, and many empirical correlations have included these in linear regression equations. Such properties include density, porosity, water content, and seismic velocities. For weak rock, Atterberg limits and clay mineralogy should be evaluated early in the site investigation, with more specialized testing for swell, squeeze, and consolidation properties perhaps warranted on the basis of the results of index tests.

(5) At this time, a recommended suite of rock property tests for tunnel project investigations should include both tensile and compressive strength, an evaluation of porosity or other measure of dilative versus compactive response, and an evaluation of rock abrasivity. Care should be taken with the core to minimize stress-relief effects and moisture loss. Sampling biases for or against very weak or very strong rock must be avoided, because it is these extremes that often define success or failure for a TBM application. For use in specific predictive approaches, particular tests can be performed, such as the various hardness tests or the suite of tests incorporated into the NTH methodology. In all cases, specified equipment for index property testing is mandatory, and suggested procedures must be followed. Guidance concerning required testing can be sought from TBM designers and consultants.

e. Empirical equations.

(1) Three commonly applied performance correlations using empirical equations developed from data on rock testing are presented below, with *PRev* evaluated in units of millimeters/revolution, F_n in *kN*, and the compressive (UCS) and Brazilian tensile (σ_{tB}) strengths expressed in units of MPa or kPa, as noted.

(2) Farmer and Glossop (1980), who include mostly sedimentary rocks in their database, derived the following equation:

$$PRev = 624\ F_n\ /\ \sigma_{tB} \tag{C-4}$$

(3) Graham (1976) derived a similar equation that uses UCS for a predominantly hard rock (UCS 140 to 200 MPa) database:

$$PRev = 3940\ F_n\ /\ UCS \tag{C-5}$$

(4) Hughes (1986) derived a relationship from mining in coal:

$$PRev = 1.667\ (F_n/UCS)^{1.2} \cdot \left(\frac{2}{D}\right)^{0.6} \qquad \text{(C-6)}$$

where D is the disc diameter in millimeter, and it is assumed that only one disc tracks in each kerf groove, the normal practice for TBM design.

e. Performance data.

(1) Rock properties and machine performance data for three tunnel projects in sedimentary rock are used to demonstrate the predictive ability of these correlations in Table C-1. Rock test results, TBM performance, and predicted penetration rates are shown in the table. Average disc forces vary directly with UCS, and the maximum load is well below the maximum load suggested for the cutters used. In each case, TBM penetration and thrust were limited by available torque or by the muck handling system capacity.

(2) The predicted penetrations are nearly always less than achieved by TBMs in operation. The Farmer and Glossop equation yields consistently higher predicted penetrations, and the Graham predictions are consistently lowest. The influence of rock test material condition is indicated by the information for the Grimsby Sandstone. Much of the original testing on this project was performed on air-dry rock. When the rock was resaturated and tested, strength reduction was evident. This uncertainty as to intact strength can clearly exert a strong influence on the penetration rate predicted.

(3) The number of equations available leads to an apparent uncertainty in *PRev* predictions. Such correlations in the public domain have generally been derived from limited databases, and caution against indiscriminant application is recommended. In general application, no single approach can be recommended; rather, use of several equations can be useful to assist in design and selection of equipment and for sensitivity studies of the relative importance of various factors. Thrust forces should, in any event, be increased by 15 to 20 percent for TBM design capacity determination.

f. Cutting coefficients.

(1) Similar equations to predict F_r are not common, largely because while thrust is often monitored during mining, drive motor amperage draw and cutterhead rpm if variable is not often recorded. The approach taken is instead to predict the cutting coefficient, C_c, the ratio of rolling to normal average force. This ratio varies within a general range of 0.1 to 0.25 and is higher for weaker rock, higher *PRev*, and for higher F_n, since F_r tends to increase faster than F_n with increasing *PRev*. C_c can be predicted as a function of *PRev* and disc diameter only, with the influence of rock strength implicit in the achieved *PRev*.

(2) Roxborough and Phillips (1975) assumed *PRev* equal to the depth of indentation or cut and derived the following equation for C_c:

Table C-1
Comparison of TBM Case Study and Predicted Penetration Rates

Project Information[1]		Rock Strength (MPa)[2]		TBM Performance		Prediction Method 1-Farmer/ Glossop, 2-Graham, 3-Hughes		
Location	Rock Unit	UCS	Brazil Tensile	F_n, kN	P/rev, mm	1 P/rev	2 P/rev	3 P/rev
Buffalo (NY)	Falkirk Dolostone	188	13.3	134	7.6	6.3	2.8	2.9
	Oatka Dolostone	139	13.0	108	10.4	5.2	3.1	3.3
Rochester (NY)	Williamson/Sodus Shale	80	(8.0)	99	10.0	-	4.9	5.7
	Reynales Limestone	128	15.0	141	6.8	5.9	4.3	5.0
	Maplewood Shale	68	(6.8)	98	10.4	-	5.7	6.8
	Grimsby Sandstone:							
	Wet	130	10.1	112	7.9	6.9	3.4	3.7
	Dry	208	6.1			11.5	4.1	4.6
Chicago (IL)	Romeo Dolostone	237	17.0	145	8.0	5.3	2.4	2.4
	Markgraf Dolostone	168	12.1	137	9.3	7.1	3.2	3.5
Austin (TX)	Austin Chalk	10	1.3	33	9.6	15.7	99.1	18.5

[1] Sources: NY and IL projects (Nelson 1983), TX project (Hemphill 1990).
[2] (8.0) and (6.8) for Brazil tensile strength are estimated as UCS/10.

$$C_c = F_r/F_n = \sqrt{PRev/(D - PRev)} \quad \text{(C-7)}$$

(3) An equation adopted in Colorado School of Mine's predictive method (Ozdemir and Wang 1979) is:

$$C_c = \tan(\phi/2);\ \phi = \cos^{-1}[(R - PRev)/R], \quad \text{(C-8)}$$

which is actually the Roxborough and Phillips equation in different form. Hughes (1986) suggests:

$$C_c = 0.65\sqrt{PRev/(D/2)} \quad \text{(C-9)}$$

In these equations, D is the disc diameter and R is the disc radius. Table C-2 records the results of an equation comparison for 432-mm-diam cutters. The similarity of the results is clear and either can be used to predict C_c and hence F_r and required power for a selected cutterhead rpm.

Table C-2

PRev, mm	Roxborough and Phillips/CSM	Hughes
4	0.10	0.09
8	0.14	0.13
12	0.17	0.15

C-3. TBM Performance Prediction via Linear Cutter Testing

a. A direct way to determine force requirements for TBM design is to perform laboratory linear cutting tests with the rotary TBM cutting process modeled as linear paths of indexed cutter indentations. Linear cutter testing has been used by contractors who plan to make their own decisions about equipment purchase or reconditioning. Such testing is expensive and not likely to be pursued for all tunnel projects. Linear cutter test results of cutter force and penetration relationships may be directly applicable to full-scale TBM penetration rate prediction. However, differences between the tested rock and the rock mass in situ, including differences in relative stiffness between the rock mass and TBM, must be considered.

b. Linear cutter test equipment is available at the Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM). CSM has developed a complete prediction method for TBM performance using field values of operating thrust, torque, cutter type, and spacing. The predictions are consistent with actual performance except when applied directly to TBM use in blocky or jointed rock masses. A match of disc cutter tip width and diameter between the field and linear cutter testing is important for accurate predictions of both forces and penetration.

C-4. Impact of Rock Mass Characteristics on TBM Performance Prediction

a. Impact of rock mass characteristics.

(1) Rock mass characteristics impact penetration rate in several ways. For example, see below:

(a) If a mixed face of variable rock strength is present at the heading, the penetration rate is more typical of the stronger rock.

(b) For good rock, penetration rate will increase as more discontinuities are present at the face. Penetration rates will be greater when discontinuities are oriented parallel to the rockface.

(c) If rock condition deterioration by geologic structure or weathering is severe, TBM thrust and torque may be reduced to promote face stability.

(2) These factors can be used to guide site investigation efforts. For example, in the common situation of flat-lying sedimentary rock, RQD determined on vertical exploratory core cannot supply information on the frequency of vertical discontinuities that can be exploited in the process of chip formation and are important for penetration rate prediction.

(3) The same factors are generally true of intact rock anisotropy, which can greatly enhance penetration rates, depending on orientation with respect to the tunnel face. Anisotropy effects may be included implicitly in intact rock prediction methods by controlling rock specimen orientation during testing. Tests such as Brazil tension and point load tests have been used for this purpose. On a larger scale, a similar effect can occur, as long as discontinuity frequency does not significantly increase rock support requirements. Increased jointing permits $PRev$ increase at decreased F_n, perhaps doubling $PRev$ when joint spacings approach cutter spacing. The effect is most important for thrust-limited mining in stronger rock.

b. Ground difficulty index.

(1) Eusebio et al. (1991) introduced a "Ground Difficulty Index" (GDI) classification scheme, developed from data for a tunnel driven in highly variable rock. Rock

mass RQD and RMR classifications were determined, and in situ Schmidt hammer testing was used to measure intact rock strength variability. From a "basic" penetration rate derived empirically from UCS and including the effect of F_n on penetration, an empirical multiplier (f1) on *PRev* can be identified depending on RMR classification, as shown in Table C-3:

Table C-3

RMR Class	f1
I	1.0
II	1.1
III	1.1-1.2
IV	1.3-1.4
V	0.7

(2) A similar approach has been taken by Casinelli et al. (1982), who suggest a correlation between specific energy (SE, in kilowatt hours/cubic meter) and RSR, based on tunnel excavation in granite gneiss as:

$$SE = 0.665\ RSR - 23 \tag{C-10}$$

for RSR > 50, with RSR the Rock Structure Rating.

(3) The EMI at the CSM has developed an equation to evaluate rock mass impacts based on RQD. Using a database for weaker rocks (UCS < 110 MPa), CSM recommends a multiplying factor, F1, to modify a basic *PRev* determined for "perfect" RQD = 100 rock as:

$$F1 = 1.0 + (100 - RQD) / 150 \tag{C-11}$$

and for stronger rocks (UCS $\geq$ 110 MPa) as:

$$F1 = 1.0 + (100 - RQD) / 75 \tag{C-12}$$

The increased importance of jointing in stronger rock is evident in these equations.

c. Impact of in situ stresses.

(1) In situ stresses that are high relative to rock strength can promote stress slabbing at the face. At typical mining rates, this response may result in an increased *PRev* if the rock is not greatly overstressed or susceptible to bursting. However, face deterioration and overbreak may develop, which must be controlled with shielding or cutterhead modifications such as false-facing in severe cases. In fact, the TBM operator usually decreases F_n and cutterhead rotation rate to improve face stability.

(2) To summarize, if rock support requirements are not changed significantly, a penetration rate (PR) increase can be expected with increased jointing present in a rock mass. Such an effect is most important to consider in very strong rock for which modest increases in PR can significantly improve the economics of a project. In practice, any PR improvement is either implicitly included within empirical correlations or ignored, in anticipation that the impact of any rock instability will dominate the performance response.

(3) As indicated in the summary presented in Table C-4, the primary impact of rock mass properties on TBM performance is on utilization, an impact that depends greatly on chosen equipment and support methods. Site investigations should be geared to address certain basic questions for equipment selection. In weak rock, mucking and rock support are major downtime sources; in very strong rock, equipment wear at high loads and cutter wear are often the major downtime sources. In either case, correct appreciation of the problem or limitation before the equipment is ordered goes a long way toward minimizing the geotechnical impacts. The actions and decisions associated with the answer to each geomechanics question are often the responsibility of the contractor, but clear assessment of each geomechanics question is the responsibility of the investigating engineers.

C-5. Impact of Cutting Tools on TBM Performance

The primary impact of disc wear is on costs that can be so severe that cutter costs are often considered as a separate item in bid preparation. The UT database indicates that about 1.5 hr are required for a solitary cutter change, and if several cutters are changed at one time, perhaps 30 to 40 min are required per cutter. Higher downtime is closely correlated with large ground water inflows, which make cutter change activities time-consuming. Disc replacement rates vary across the cutterhead, with low rolling distance life associated with center cutter positions where tight turning and scuffing reduce bearing life and vibrations can cause particularly high rates of abrasive wear. For relatively nonabrasive rock, rolling distance life for cutters in gage and face positions are comparable. However, gage replacement rates are higher in terms of TBM operating time because the travel path is longer and the cutters "wash" through muck accumulations. Gage cutter rolling

Table C-4
Impacts of Geotechnical Conditions on TBM Operations

Major Geotechnical Conditions	Consequences/Requirements
Loosening loads, blocky/slabby rock, overbreak, cave-ins	At the face: cutterhead jams, disc impact loading, cutter disc and mount damage possible, additional loss on available torque for cutting, entry to the face may be required with impact on equipment selection, recessed cutters may be recommended for face ground control. In the tunnel: short stand-up time, delays for immediate and additional support (perhaps grouting, hand-mining), special equipment (perhaps machine modifications), gripper anchorage and steering difficulty, shut-down in extreme cases of face and crown instability. Extent of zones (perhaps with verification by advance sensing/probe hole drilling) may dictate shield required, and potential impact on lining type selection (as expanded segmental linings may not be reasonable), grouting, and backpacking time and costs may be high.
Groundwater inflow	Low flow/low pressure - operating nuisance, slow-down, adequate pumping capability high flow and/or high pressure - construction safety concerns, progress slow or shut-down, special procedures for support and water/wet muck handling, may require advance sensing/probe hole drilling. Corrosive or high-salt water - treatment may be required before disposal, equipment damage, concrete reactivity, problems during facility operation. Equipment modifications (as water-proofing) may be required if inflow is unanticipated - significant delays.
Squeezing ground	Shield stalling, must determine how extensive and how fast squeeze can develop, delays for immediate support, equipment modifications may be needed, if invert heave and train mucking - track repair and derail downtime.
Ground gas/hazardous fluids/wastes	Construction safety concerns, safe equipment more expensive, need increased ventilation capacity, delays for advance sensing/probing and perhaps project shut-down, special equipment modifications with great delays if unanticipated, muck management and disposal problems.
Overstress, spalls, bursts	Delays for immediate support, perhaps progress shut-down, construction safety concerns, special procedures may be required.
Hard, abrasive rock	Reduced *PRev* and increased F_n - TBM needs adequate installed capacities to achieve reasonable advance rates, delays for high cutter wear and cutterhead damage (especially if jointed/fractured), cutterhead fatigue, and potential bearing problems
Mixed-strength rock	Impact disc loading may increase failure rates, concern for side wall gripping problems with open shields, possible steering problems.
Variable weathering, soil-like zones, faults	Slowed progress, if sidewall grippers not usable may need shield, immediate and additional support, potential for groundwater inflow, muck transport (handling and derails) problems, steering difficulty, weathering particularly important in argillaceous rock.
Weak rock at invert	Reduced utilization from poor trafficability, grade, and alignment - steering problems.

distance life is notably reduced in highly abrasive rock mining. Database information indicates that TBM penetration rate is generally unaffected by disc cutter abrasion until the wear causes about a 40-mm decrease in disc diameter. For additional amounts of wear, penetration rate may only be maintained with increased F_n. If thrust is not increased, the penetration rate achieved may be reduced by 15 to 25 percent. Normal cutterhead maintenance checks will guard against this happening. It is particularly important for the contractor to develop a management plan to promote cutter life, since high cutter loads associated with worn cutters can result in higher disc and bearing temperatures and in more bearing and seal failures. Regular inspection and planned replacements are required to maximize disc life, reduce cutter change downtime, and minimize cost and schedule impacts. Cutter change downtime can also be expressed on the basis of shift time. For nonabrasive rock, the cutter downtime may be on the order of 3 percent. For highly abrasive rock, however, cutter changes may require more than 20 percent of all shift time. Cutter change downtime can also be recorded as hours required per meter of excavation. For nonabrasive rock, average cutter change downtime was 0.02 to 0.05 hr/m. For more abrasive rock, downtime may increase to more than 0.2 hr/m. Tight alignment curves can decrease cutter disc life significantly. The EMI at the CSM has developed an equation to evaluate alignment curve radius impacts on cutter life. CSM recommends a multiplying factor, $F2$, to modify an expected "normal" cutter life for alignment curves of radius R, in meters determined for "perfect" RQD = 100 rock as:

$$F2 = 1.0 - 23/R \tag{C-13}$$

The recent trend toward larger disc diameter means that cutters are heavier, and equipment must be installed to facilitate cutter transport and installation. Wedge-lock housing has been developed that makes cutter changes much easier and that has proven to be very durable. Other improvements include rear-access cutters that do not require access to the front of the cutterhead for replacement. In cases of face instability, these cutters greatly improve safety but are more expensive and take more time to replace.

In abrasive conditions, significant wear of the cutter mount and hub can occur with reduced disc bearing life. In relatively nonabrasive rock, 6 to 10 discs can be refit on each hub before repair is necessary. However, in abrasive sandstone, a rate of only 1 to 3 discs per hub may be typical. In very abrasive rock, tungsten carbide cutters may be used at increased expense. Most of the databases on cutter replacement rates and costs are proprietary. The largest public-domain database for abrasive wear rate prediction can be accessed through the NTH (1988) method, but specific rock tests must be performed that require special equipment. If abrasive conditions are anticipated, it is important to submit samples for testing by machine manufacturers, contractors, and specialized consultants.

C-6. The EMI TBM Utilization Prediction Method

a. Several databases can be accessed to assist in evaluations of TBM utilization. In the future, a complete simulation computer program including all components of TBM construction operations will be available through the Texas database analysis.

b. The EMI CSM (Sharp and Ozdemir 1991) also has developed an approach to evaluate TBM utilization via analysis of a proprietary database. To account for delays associated with thrust cylinder piston restroke, a parameter $F3$ is recommended as:

$$F3\ (hr/m) = 0.030\ (hr/m) + (409\ m{-}hr)/\,R^2 \tag{C-14}$$

where R is the radius of alignment curvature in meters. For straight tunnel sections, this equation predicts about 2.7 min per 0.45-m stroke cycle. For tight curves of perhaps 150-m radius, this stroke reset time increases to 4.4 min. To account for unscheduled maintenance and repairs, a factor $F4$ (in units of delay hours) is evaluated as:

$$F4\ during\ start\text{-}up = 1.0\ hr\ per\ TBM\ mining\ hr$$

and

$$F4\ following\ start\text{-}up = 0.324\ hr\ per\ TBM\ mining\ hr.$$

c. The start-up period is identified as a learning curve with shift utilization deceasing to a fairly constant value corresponding to production mining. Scheduled maintenance, including cutterhead checks and TBM lubrication, should be evaluated at 0.067 delay hours per TBM mining hour.

d. Surveying delays are discretely accounted for in the CSM approach. Normal delays for straight tunnel sections are minimal at 0.0033 hr per meter of bored tunnel. For alignment curves, survey delays are evaluated as:

$$Survey\ delay\ (hr/m) = 0.0033 + 192\ m{-}hr\ /\ R^2 \tag{C-15}$$

where R is the radius of curvature in meters. For a 150-m-radius curve over a 200-m-long tunnel length, survey delays of about 2.5 hr should be expected by this equation.

e. For minimal nuisance water inflows, delays can be expected at a rate of about 0.0056 hr per meter of bored tunnel. For conditions of inflow up to about 3 to 4 m^3/min/m of tunnel, delays on the order of 0.085 hr/m of bored tunnel should be expected. Excess water inflow and grouting precipitates additional delays that are higher for increasing inflow volumes and for low gradient to downhill tunnel driving. For example, for downhill grades, delays will multiply to 2 hr/m of tunnel at inflow rates in excess of 13 to 15 m^3/min/m of tunnel.

f. Delays associated with the tunnel mucking system can be estimated considering tunnel gradient, direction of drive, and expected mucking system. Table C-5 shows some general guidelines.

Table C-5

Tunnel Description	Mucking Method	Delay hr/m
Start-up Driving	Trucks	0.115
Production Driving		
-15° to -1° down	Conveyor	0.071
-1° to +3°	Train	0.056
+3° to +15° uphill	Conveyor	0.071

Delays associated with extending utility lines will also depend on tunnel grade:

$$\textit{Utility Delays (hr/m of tunnel)} = 0.030 + 0.0013\,G \qquad \text{(C-16)}$$

with G the tunnel grade defined as the angle (in degrees) of TBM driving above (>0) or below (<0) the horizontal. Delays associated with installing temporary support accumulate as a function of rock mass quality. In the CSM approach, Rock Support Category (RSC), similar to the classes resulting from RMR classification, is used. See Table C-6. Labor delays are evaluated to cover time spent on shift changes, safety meetings, lunches, etc. CSM recommends using 2.5 percent of the overall shift time as labor-delay downtime.

Table C-6

RSC Category	Delay (hr/m of bored tunnel)
I	0
II	0
III	0
IV	0.028
V	0.043

g. The CSM approach includes all aspects of TBM operations, and its validity for general application resides in the proprietary database used to derive these equations. However, the cutter life and *PRev* prediction methods are not in the public domain. Until more data analysis is completed in the public domain, however, the CSM methodology is recommended as a way to evaluate decisions required for project alignment and equipment selection.

C-7. The NTH TBM Performance Prediction Methodology

a. The Norwegian Institute of Technology (NTH) has developed the most thorough published predictive approach for TBM performance (NTH 1988). The NTH method is certainly the most systematic method available in public domain and includes all desirable aspects of TBM design and operation, including thrust, torque, rotation rate, cutterhead profile, disc spacing and diameter, and disc bluntness.

b. Intact rock tests required in the methodology include three specialized tests for abrasivity value (AV), brittleness (S_{20} from the Swedish Brittleness test), and drillability (the Sievers J Value). Derived rock parameters include the Drilling Rate Index (DRI) and Cutter Life Index (CLI). The F_n versus *PRev* relationship is nonlinear, and the concept of "critical thrust" is incorporated as a normalizing parameter. Various factors are offered to modify the calculated *PRev*, thrust, and torque for differences in cutter diameter and kerf spacing.

c. The NTH method is derived for a database consisting primarily of experience in Scandinavian rocks and may be considered more suitable for application to tunneling in igneous and metamorphic rock. Certain "rules" for TBM design are also incorporated into the figures presented:

- Cutterhead rpm is established by maximum gage cutter rolling velocity (Table C-7):

Table C-7

Disc Diameter mm	in.	Max. Gage Velocity m/min
356	14	100
394	15.5	120
432	17	160

- Disc groove average spacing (TBM radius/number of discs), assuming only one disc cutting each groove, is set at about 65 mm.

- Maximum cutter loading is dependent on disc diameter (Table C-8):

Table C-8		
Disc Diameter		Max. Disc Cutter Load
mm	in.	kN
356	14	140-160
394	15.5	180-200
432	17	220-240
483	19	280-300

- Installed cutterhead power is expected according to the relations shown in Table C-9:

Table C-9		
Cutter Diameter		Installed Power
mm	in.	kW
356	14	700 + 140 (D - 5 m)
394	15.5	850 + 170 (D - 5 m)
432	17	1,050 + 200 (D - 5 m)
483	19	1,800 + 360 (D - 5 m)

d. The method for *PRev* prediction relies on DRI values that can be tested through NTH, although correlations between DRI and UCS (determined on 32-mm-diam cores) are presented for some rock types in Table C-10. Note that low DRI values correspond to difficult drilling, so that low DRI generally corresponds to high UCS.

Table C-10		
Rock	DRI Range	Range in UCS, MPa
Quartzite	20-55	>400-100
Basalt	30-75	
Gneiss	30-50	300-100
Mica Gneiss/ Coarse Granite	30-70	240-70
Schist/Phyllite	35-75	150-50
Med/Fine Granite	30-65	280-120
Limestone	50-80	110-70
Shale	55-85	30-10
Sandstone	45-65	180-100
Siltstone	60-80	100-20

e. The NTH method relies on CLI, the cutter life index for disc replacement rate estimation. The NTH database includes the information on CLI shown in Table C-11:

Table C-11	
Rock	CLI Range
Quartzite	0-8
Basalt	25-75
Gneiss	2-25
Schist/Phyllite	10-40
Med/Fine Granite	30-65
Limestone	70 to >100
Shale	40 to >100

For specific rock types encountered on TBM projects, samples should be submitted to NTH for CLI evaluation.

f. The NTH approach to TBM performance estimation, summarized herein, represents a discussion of the general methodology. The many figures and tables included in the source manual are reduced to close approximations for presentation in this document. If precise values of the identified factors are desired, the user should consult the NTH project report.

g. In the NTH method, the *PRev* prediction is achieved as:

$$PRev = [F_n/M_1]^b \qquad \text{(C-17)}$$

with M_1 found as a "critical thrust," evaluated for *PRev* = 1 mm, and b is the "penetration coefficient."

The M_1 is found from a sequence of figures in the NTH report and is a function of DRI and factors associated with disc diameter (k_d), disc groove spacing (k_a), and rock mass fracturing (k_s). The k_s factor effectively modifies the thrust versus penetration relationship for a given intact rock, such that the more fractured a rock mass is, the higher the *PRev* achieved for a given F_n. This factor is also used in torque calculations since, in fractured rock, torque demand increases with increased penetration. The M_1 increases with increasing cutter diameter and spacing and decreases with higher DRI and increased fracturing (high k_s).

The k_d factor is found as shown in Table C-12:

Table C-12

Disc Diameter mm	in.	k_d
356	14	0.84
394	15.5	1.00
432	17	1.18
483	19	1.42

The k_a factor can be approximately found as:

$$k_a = 0.35 + s / 100 \tag{C-18}$$

where s is the average disc spacing, in millimeters. The k_s factor is a function of a classification made on the basis of spacing and strength of discontinuities (joints or fissures) present in a rock mass. Joints are defined as discontinuities that are open, or weak if filled, and continuous over the size of the excavation. Fissures generally include bedding and foliation—discontinuities with somewhat higher strength than joints. If a rock mass contains no discontinuities, or those present are filled or healed so as to be of very high strength, the material is considered massive rock (Class 0). Table C-13 indicates the general range of k_s expected for rock masses dominated by various classes of jointing or fissuring. The low end of each k_s range corresponds to discontinuities generally trending normal to the excavated face or with strike parallel to tunnel axis. The high end range of k_s corresponds to discontinuities favorably oriented for chip formation, i.e., parallel to the excavated face or with relative strike perpendicular to the tunnel axis. Users of the NTH method should consult the referenced manual for a complete treatment of k_s selection. For joints at close spacing, it is likely that face instability will dominate TBM operations, and no k_s is assigned.

h. In the NTH database, Class 0 - I rocks were generally gneiss, quartzite, and basalt. Classes III and IV are predominantly populated by schists, phyllites, and shales. The penetration coefficient, b, is found as a function of M_1, disc spacing, and disc diameter. The coefficient varies from about 1.0 to greater than 4.0; b is highest for large M_1 values and disc diameter, and more closely spaced cutter grooves or, in general, for stronger rock. Correct selection of b is very important to the NTH approach as it is the exponent used to establish the basic force/penetration relationship. Reference should be made to NTH for appropriate rock testing and selection of both M_1 and b for site-specific applications. With all parameters identified, it is possible to evaluate *PRev* and PR, the penetration rate in terms of meter/mining hour, and to design a TBM for required thrust and *PRev*.

i. To evaluate torque requirements, the NTH method uses the following equation:

$$F_r = F_n \sqrt{PRev} \tag{C-19}$$

where C is the cutter constant, a function of disc diameter, k_s, and cutter sharpness. In application, the NTH method sometimes has indicated lower penetration rates than were achieved. This difference is due to the method being based upon laboratory test results and not in situ strengths. The NTH methodology includes an approach to estimate cutter replacement rates. The prediction is based on the Cutter Life Index (CLI), a compound parameter depending on the Abrasion Value (determined for steel rings) and the Siever's J-value (a drillability test).

j. Average disc life, L_h, in units of TBM mining hours per cutter, is found as:

$$L_h = DL\ k_\phi\ k_{rpm}\ k_N\ k_{min} / N \tag{C-20}$$

Table C-13

Joints Class	Joints Spacing	Fissures Class	Fissures Spacing	k_s
0	>1.6 m	0	>1.6 m	0.36
0-I	≈ 1.6	I	0.8-1.6	0.5-1.1
I	0.8-1.6	II	0.4-0.8	0.9-1.5
I-II	0.4-0.8	II-III	0.2-0.4	1.1-1.8
II	0.2-0.4	III	0.1-0.2	1.3-2.3
II-III	0.1-0.2	III-IV	0.1-0.05	1.9-3.0
>III	not valid	IV	<0.05	3.0-4.4

Disc Diameter		K_s Range	C	
mm	in.		blunt	sharp
356	14	from <0.75 up to ≈4.0	0.038 0.070	0.044 0.082
394	15.5	from <1.0 up to ≈4.0	0.034 0.050	0.041 0.060
432	17	all	0.025	0.033
483	19	all	0.018	0.027

where N is the number of discs, and DL is the "Disc Life," found as shown in Table C-14:

Table C-14

Disc Diameter		
mm	in.	DL, TBM hrs
356	14	8.6 CLI
394	15.5	12.4 CLI
432	17	17.4 CLI
483	19	26.3 CLI

k. The various correction factors are defined as follows. The correction factor k_ϕ is a correction for TBM diameter and cutterhead type, required since the proportion of gage cutters decreases as TBM diameter increases, and because cutters on flat-faced cutterheads have longer life than do cutters on domed cutterheads. Values for k_ϕ are shown in Table C-15.

Table C-15

	k_ϕ	
TBM Diameter, m	Domed	Flat
3	0.92	1.04
5	1.19	1.34
7	1.40	1.58
10	1.67	1.87

(2) The correction factor k_{rpm} is for cutterhead rotation rate, required since the faster the rpm, the higher the rolling velocities and the shorter the disc life. This correction factor is found as

$$k_{rpm} = 38/(D\ rpm) \qquad \text{(C-21)}$$

where rpm is the cutterhead rotation rate in revolutions per minute and D is the diameter of the TBM in meters.

(3) The correction factor k_N is developed for TBMs where disc spacing is not at the 65 mm assumed. With more discs at smaller spacing, a longer life is expected. If s is the average disc spacing in millimeters (TBM radius divided by the number of cutters), k_N is found as

$$k_N = 65/s \qquad \text{(C-22)}$$

The correction factor k_{min} is designed to correct the estimated cutter life for the presence of abrasive minerals such as quartz, mica, and amphibole. This correction factor is calculated as:

$$k_{\min} = k_{quartz}\ k_{mica}\ k_{amph} \qquad \text{(C-23)}$$

with the correction factors for individual minerals found to sufficient accuracy by interpolation from values in Table C-16 with the mineral content defined on a volume percent basis:

Table C-16

Mineral Content, Volume %	k_{quartz}	k_{mica}	k_{amph}
0	1.0	1.0	1.0
10	0.74	0.78	0.90
20	0.67	0.72	0.58
30	0.65	0.67	0.46
40	0.65	0.65	0.38
50	0.65	0.62	0.34
≥60	0.65	0.60	0.31

l. Using results from *PRev* calculation, it is also possible to express cutter life in terms of cutter rolling distance or cubic meters of rock excavated per cutter change. By the NTH database, typical 394-mm-diam rolling distance life varies from 200 to 1,000 km for highly abrasive rock, and up to 5,000 to 10,000 km for nonabrasive rock. Cutter life is reduced by 30 percent for 356-mm-diam cutters and increased by 50 to 65 percent for 432-mm-diam cutters. Cutters on flat cutterheads have 10-percent longer life than on domed cutterheads, and constant section cutters last 10 to 15 percent longer than do wedge section cutters with similar amounts of steel in the disc rings. Mining around tight curves reduces cutter life by about 75 percent.

m. The NTH methodology also permits utilization and advance rate prediction in a manner similar to that used in the CSM approach as outlined below:

- The mining time, T_b, can be evaluated from the *PRev* established previously.

- Regrip time, T_t, estimated as about 5.5 min per reset cycle.

- The cutter change downtime, T_k, is estimated using the output from cutter life calculations. For cutter diameters $\leq$ 432 mm (17 in.), NTH suggests using 45 min per cutter change. For larger cutters, a suggested 50 min per change should be used.

- The TBM maintenance downtime, T_{TBM}, is estimated as 150 shift hours per kilometer of mined tunnel.

- The time required for maintenance and repair of backup systems, T_{bak}, is estimated from the table below.

- Miscellaneous downtime, T_a, includes other activities as waiting for return of empty muck cars, surveying, electrical installations. The T_a is related to type of back-up equipment and can also be estimated from information in Table C-17.

Table C-17

	Shift hr/km mined tunnel	
Back-up System	T_{bak}	T_a
Single track	40	185
Double track	90	95
Trackless	55	95

The sum of these time increments equals the shift time, from which utilization and advance rate can be calculated. The NTH method also includes approaches to evaluate project cost, support requirements, and additional information on all components of downtime, site investigations, and interpretation of geologic conditions.